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1. REPORT DATE (DD-MM-YYYY) 27/5/08		2. REPORT TYPE Final Technical Report		3. DATES COVERED (From - To) 1/10/02-15/5/08	
4. TITLE AND SUBTITLE Design and Testing of a Diver Thermal Protection Garment				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER NOOO14-02-1-0278	
				5c. PROGRAM ELEMENT NUMBER NOOO14-02-1-0278	
				5d. PROJECT NUMBER NOOO14-02-1-0278	
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				5f. WORK UNIT NUMBER NOOO14-02-1-0278	
				5g. WORK UNIT NUMBER NOOO14-02-1-0278	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Center for Research and Education in Special Environments, Department of Physiology and Biophysics, School of Medicine and Biomedical Sciences at the University at Buffalo, Buffalo, NY 14214				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Research Foundation State of New York Attn. Dr. Charles Kaars Assistant Vice President, Sponsored Projects Services 402 Crofts Hall University at Buffalo, Buffalo, NY				10. SPONSOR/MONITOR'S ACRONYM(S) ONR	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Distribution Unlimited					
13. SUPPLEMENTARY NOTES none					
14. ABSTRACT <p>Missions in cold and hot water have to be planned to insure thermal protection to prevent loss of diver capability. The objective of this project was to design, develop and test a diver thermal protection system (DTPS) that would eliminate the thermal constraint, and protect free swimming divers in waters from 5°C to 40°C at rest and during exercise at depths to 350 fsw. The DTPS developed met the objectives, protecting divers in waters from 5°C to 40°C at rest and during free swimming. The DTPS is self contained, has few moving parts, does not use consumables, and can run 200 hrs without maintenance. The DTPS can be powered from batteries and other power sources, including surface supply. The battery modules developed under this grant can provide protection for 8-12 hrs in cold and 2-4 hrs in warm. The DTPS also acts as a total body and regional calorimeter. Importantly the DTPS automatically protects the diver via a controller in cold and hot water. The DTPS is protected and currently available for commercialization and can be adapted to many diving environments.</p>					
15. SUBJECT TERMS diver thermal protection, hot water, cold water, metabolism, diving performance, heat balance, power requirements, battery technology, wet suit, pressure, electrical heating/cooling, tube suit, thermal garment					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 14	19a. NAME OF RESPONSIBLE PERSON David R. Pendergast
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (Include area code) 716-829-3830

20080603196

FINAL TECHNICAL REPORT

GRANT #: N00014-02-1-0278

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GRANT TITLE: Design and Testing of a Diver Thermal Protection Garment

AWARD PERIOD: 1 October 2002 – 15 May 2008

OBJECTIVE: The major objective of this project was to design, develop and test a diver thermal protection system that would protect free swimming dives in both warm and cold water using an engineering approach to identify existing, but underutilized, technology and intergrading it into a diver thermal protection system. The specific objectives were to maximize the passive thermal protection to minimize the requirement of an active system, and to develop and active diver thermal system that together would protect a free swimming diver in water of temperatures from 5°C to 40°C at rest and during exercise at depths down to 350 fsw, while maintaining core and skin temperatures.

APPROACH: This project was primarily an engineering project to meet the objective of the project objective stated above. Initially collaboration was formed with Hamilton Sundstran Space System (HSSS), an engineering company, that had extensive experience with thermal protection in space. Together initially with HSSS and later with only the UB team potential technical solutions to thermal protection were identified and their application to the diving environment was evaluated. From this evaluation technologies were selected for bench testing and eventually intergraded into the diver thermal protection system. Once the unpromising and promising technologies were identified, the diver thermal protection system was designed, and subsequently built and tested over the range of conditions outlined in the objectives. Testing was performed in the Center for Research and Education in Special Environments in a water bath, annular swimming pool and hyperbaric chamber. In addition to the diver thermal protection system, power supplies also had to be investigated and tested. Finding no potential alternative a battery pack system was developed and tested to power the diver thermal protection system in the free swimming mode.

ACCOMPLISHMENTS: The major accomplishment of this project was the development of a diver thermal protection system (DTPS) which has been extensively tested and provides thermal protection to free swimming, as well as surface supplied divers, in water temperatures from 5-40°C at rest and during exercise at the surface and at depth. In addition to the DTPS this project has provided the funds and support for the education of 1 Postdoctoral Fellow, 1 PhD in engineering, 2 Masters degrees in engineering and independent research experience for at least 6 undergraduates and 2 medical students. We have published and presented 10 abstracts at Under Sea and Hyperbaric Medicine annual meeting. We have published 6 papers in reviewed journals and have two under

preparation. We have prepared eight internal reports on technologies that were tested and rejected. There has been one patent issued and one is under consideration.

The DTPS has been presented annually at the Navy Progress Review Meetings and briefed to the Navy Experimental Diving Unit on three occasions and to the Swimmer Delivery Vehicle teams at one working session. We are currently working with three companies for potential commercialization of the system and with SDV development team to apply the DTPS to divers in an SDV environment.

The specific accomplishments of this project were the rejection of several tested technologies (1) and development of: 2) a new passive insulation wet suit, 3) development of a six zoned tube suit, 4) development of a active heating and cooling system to perfuse the tube suit, 5) development of an electrical isolation system for the active heating cooling unit, 6) development of a portable battery modular system to power the DTPS in free swimming divers 7) surface supply system for the DTPS and 8) Pressure compensation system.

(1) The engineering evaluation of technologies that had potential application to diver thermal protection yielded several that we bench tested to determine their efficacy in a DTPS. First over twenty forms of insulations (from foam neoprene to syntactic foam to aerogels) were selected and tested in a thermal conductivity meter at the surface and at depth. None of these materials met the requirements and this work led to the development of the "UB Hybrid Insulation" that is described below as a product.

It was originally proposed to combine fuel cell technology with phase change materials to generate and store power to be used for heating and cooling. In the case of the fuel cell, first in spite of the fact that many were advertised and fuel cell technology is being touted as a modern technology, they were either not available or extremely expensive. We also discovered that other groups that had tried this technology had abandoned it. We did locate and purchase two fuel cells from China and built a mock up bench version of the DTPS. This system was tested extensively and incorporated into a design of the DTPS. This system did not function as there were losses of O₂ and hydrogen that were integral to the fuel cell itself and the power production was significantly lower than expected. In addition the fuel cell was unreliable. For all these reasons this technology was rejected. Fuel cells with greater or lesser power may be successful, however in the range required to heat/cool divers the technology is neither mature enough nor does it have the power density of modern batteries. (see Balikowski JR. Reynolds DG 2003) .

Based on the design criteria of having a DTPS that would both heat and cool we evaluated a compact refrigeration unit. We extensively tested a vapor-compression cycle unit for use in the DTPS in the cooling mode. The study varied the compressor speed, expansion valve orifice spring position, and the flow rate of water through the evaporator coil. With this system we could remove maximally remove up to 200 W of heat with a coefficient of 1.5 with this unit. Although this unit was reliable the cooling was significantly less than needed, the unit generated noise and position and temperature sensitive, thus eliminating it from consideration in the diving environment. This is completed as an internal report (Reynolds DG, Senior Design Projects)

(2) Insulation

The papers and reports that relate to the development of the UB hybrid insulation are Felske JD., Bardy E., Cuviallo R., Walczk J., Reynolds D and Janish J and their citations are shown below. The extensive evaluation of the thermal conductivity and flexibility of specific insulation material did not reveal one that met the criteria of being able to be made into a wet suit and /or did not have sufficient insulation. Based on this a hybrid insulation was made from syntactic foam and Aspen aerogel and a process invented to produce the hybrid material (see Figure 1). This material and process has been issued a patent: Patent number: 10/645,726 Process for enhancing material properties and materials so enhanced. US Patent No. 7,101,607, Issued 9/5/2006. The essence of this material is that although it does not have superior insulation to foam neoprene at the waters surface, it does not compress with depth and thus maintains its insulation characteristic, as opposed to foam neoprene which at 50 fsw has lost $\frac{1}{2}$ of its insulation (see Figure 1). We thus conclude that at depths greater than 50 fsw the new UB hybrid wet suit may have some utility. However, even this insulation did not fully protect the diver, thus an active system was developed. This system, described fully below, could protect divers in a standard wet suit which has greater ergonomic characteristics, and thus the UB Hybrid suit development was put on hold and all future testing done with a standard wet suit.

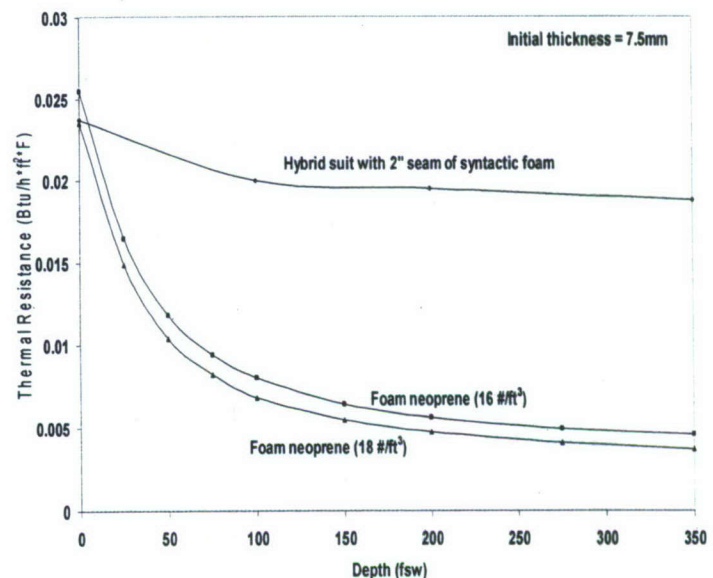


Figure 1. UB Hybrid wet suit on the left and its performance as a function of depth on the right.

Development of the six zone tube suit (see Figure 2). The human body can be divided into segments, each of which has a different thermal balance, as some zones have high heat production due to their muscle mass, some have great heat loss due to their ratio of surface area to heat capacity, and others that have heat loss and gain via the convective movement of heat by the circulation from zone to zone. In addition, protecting the hand and feet in cold water and the core/brain in hot water has been shown to be the critical areas to be protected. To optimize thermal protection a six zone concept was developed (hands, feet, legs, arms, torso, head) to insure

protection of the required areas and minimize heat loss/gain. In spite of the water temperature the diver was immersed in some zones may give off heat and others may require heat, by having separate zones each zone received only the heat it required, and the heat lost from any zone would be conserved as it would be pick up and re-circulated in the system.

(3) The first step in this process was to select a liquid garment. To this end we worked with HSSS and MedEng. As described above the HSSSS negative pressure system did not function and was abandoned for the MedEng tube suit. In both theoretical calculations and actually measurement the tubes configured as developed between UB and MedEng gave equal heat exchange to that of panel suits and thus the tube suit was adopted. In addition data supplied by MedEng and confirmed by our own experiments showed that at flow of water through the tubes of 500 ml/min optimized heat exchange, and the maximal number of tubes was sewn into the suit by Med Eng, thus maximizing heat exchange to each zone. Due to the optimal flow the over all flow to the hands and feet had to be 1,000 ml/min, to get 500 ml/min to each hand and foot. As part of these experiments we determined the pressure drop across the zone in order to determine the perfusion pressure that we would need to perfuse the tube suit. These data are incorporated in two internal reports (Walczyk J., Bessel KWR)



Figure 2. MedEng tube suit.

The next question to be answered was what temperature the water circulating through the tube suit should be set at to thermally protect divers in water of different temperatures. Based on experiments performed in air we hypothesized that we could keep the hand and feet vasodilated, and thus thermally protected, in cold water by heating the torso to 40°C. We performed these experiments on 6 subjects and found that the hand and foot temperature dropped as though they were not protected, thus we abandoned this approach.

To then test the question of what temperature of tube suit perfusion was required we used surface supply heater/chillers that perfused the tube suit worn under a standard wet suit (6.5 mm) and varied

their set temperature. Our first attempt was to use warm water when the subject was immersed in cold water and cool water when he was immersed in hot water. A matrix of immersion temperatures was determined in six subjects (see Figure 3). These experiments discovered that we could protect the diver in water temperatures of 5-40°C with 35 to 25°C water, maintaining core temperature at 37°C and skin temperatures between 25 and 35°C, thus meeting the Navy's established criteria. This system of perfusing consumed significant electrical energy and was deemed to not be ideal. We then decided to clamp the skin temperature at 30°C, which is the critical temperature, by perfusing all zones of the tube suit with 30°C which was shown to provide protection over a wide range of temperatures. This perfusion temperature would also, if it worked, make the control of the heating and cooling system simpler. This experiment revealed that as long as we had sufficient heating and cooling power, which we did, we could protect the diver in all water temperatures.

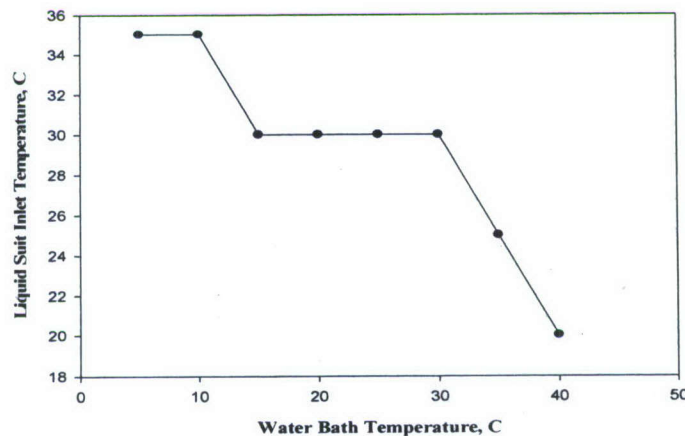


Figure 3. The tube suit perfusion temperature as a function of immersion temperature to maintain thermal balance in divers wearing a standard wet suit with surface supplied water.

(4) Based on the thermal requirements measured in the experiments described in (2) above and the tube suit configuration described in (1) above an active heating/cooling water circulation system was developed, tested and submitted for patent protection (Patent Application Serial No. 11/126,011, Filed May 10, 2005 for BODY THERMAL REGULATION/MEASUREMENT SYSTEM claiming priority of Provisional Application Serial No. 60/569,703, filed May 10, 2004. Inventors Mollendorf/Pendergast: R-5870; NP Reference No: 19226/2391). In addition two internal reports were written (Bessel KWR and Mollendorf JM, Pendergast DR.)

The first step in this process was to reject technology that did not fit the design criteria as outlined above. After this the specific equipment that was identified as required were circulating pumps (n = 6) and thermal electric coolers (initially decided to be 5, and now upgraded based on experimental data to 7). In the latter case the TEC, actually heat and cool based on the polarity of current provided to them and operate at a voltage of 24 – 32 volts DC, with 32 being the optimal. It was decided to incorporate all components of the Diver Thermal Protection System (DTPS) into a backpack that could be worn by a free swimming diver and also carry the scuba tanks necessary to breathe underwater. To insure redundancy in the system the 7 TEC (T) operate in parallel, thus if one miss functions the other would continue heating/cooling. In addition the TECs do not use any consumables, except electrical power, and operate continuously as long as power is available. To

make control simple and again provide redundancy in the system the water return from the tube suit enters a common manifold (M) and is drawn through the TECs where it is heated/cooled. The heating/cooling by the TEC is controlled by an electronic controller to set the water temperature in a common manifold from which water is circulated to the six zones of the tube suit by the 6 pumps (P) in the system. Thus the system has few moving parts, consumes only electricity and has redundancy in operation. Although the system weights about 28 lbs in air, it is neutrally buoyant in water. There is tubing with quick disconnects that connect the output of the 6 pumps to a distribution block on the wet suit, which in turn has quick disconnects that connect the tube suit zones to the distribution block in the wet suit (OD).

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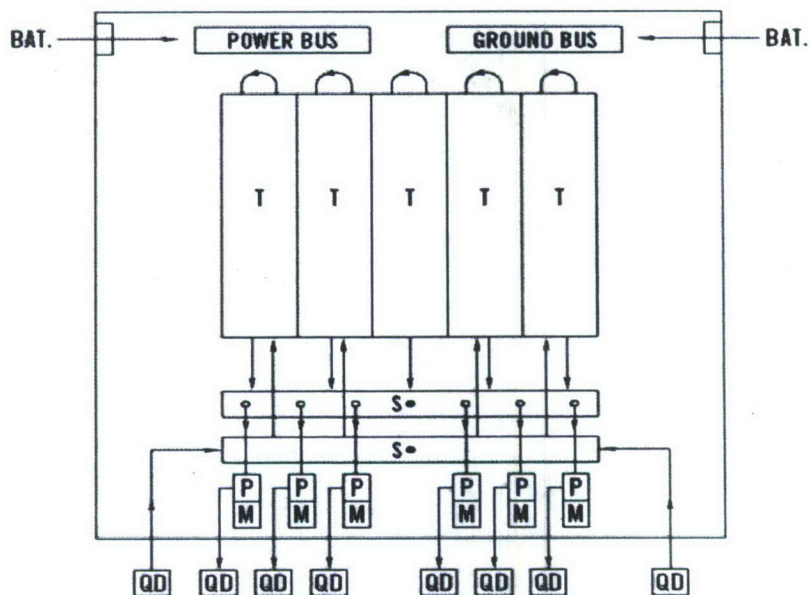


FIG. 2

Figure 4. Schematic representation of the DTSP for heating/cooling showing the TECs (T) and pumps (P) and manifold (M) as well as piping to the tube suit (QD).

Using this portable DTPS we have demonstrated in 8 divers that the DTPS could thermally protect divers in water temperatures from 5-40°C for over a 3 hr period. If sufficient power was supplied from a surface supply system, the DTPS could keep the diver warm/cool indefinitely which we have demonstrate in a few divers. We have performed these tests in resting divers (Bardy et al 2007) and in exercising divers (Pendergast 2008).

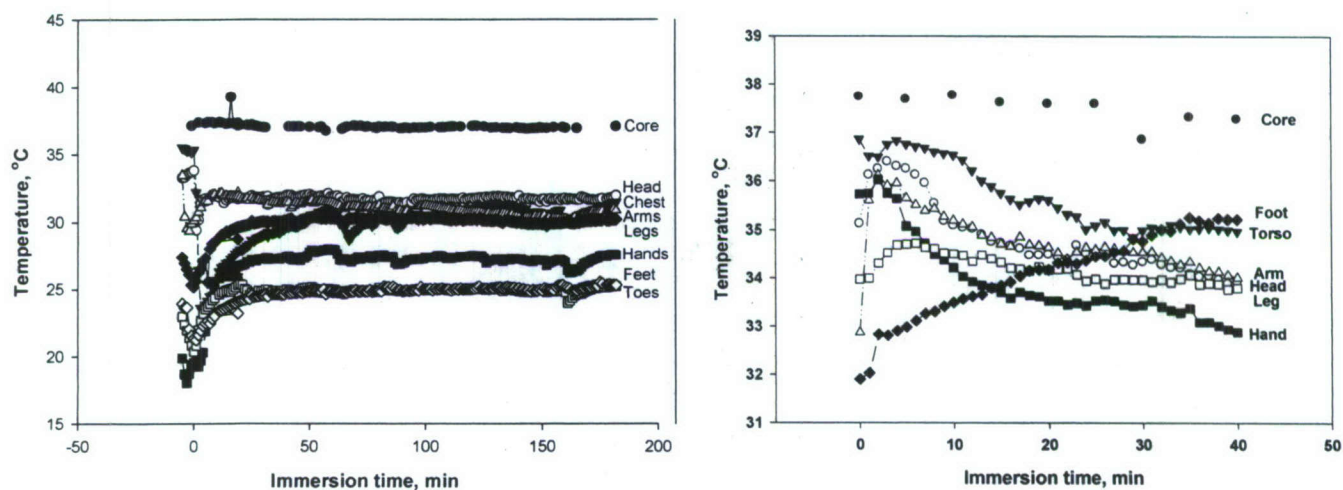


Figure 5. Core and skin temperatures during exposure to cold (left) and warm (right) water showing that both core and skin temperatures were maintained by the DTPS in the desired range.

(5) The use of electrical power in an aquatic environment requires protection for the subjects. The Navy regulations for hand-held devices were used in the development of an electrical protection system for the DTPS. This system was designed to protect against an electrical signal that would occur directly across the heart itself as the most conservative approach. This system was developed by the CRESE team in conjunction with the engineering group at NEDU and its complete description is incorporated in an in-house report by Mollendorf and Pendergast (see below). This system was subsequently tested in un-manned experiments in water to insure that the ground fault system triggered when violated.

(6) As the DTPS was designed to be free swum, a portable electrical power system was required. As fuel cell technology was rejected, the development was put into battery technology, the power density of which had dramatically increased since the original proposal. The first generation of batteries developed was based on lithium polymer battery technology, as it was considered the safest having the highest power density. We build battery modules from the batteries incorporating 64 batteries into a module incased in a square aluminum box, 6 in by 6 in by 28 in long. Two of these modules were built and tested in the free swimming mode in both cold and warm water. Although the battery power lasted 3-4 hrs in the cold, they only lasted 30-45 min in the warm water. In addition, we learned the balancing of the charging and discharging of individual battery modules was problematic, with some cells being damaged as they were discharged too deeply.

At this stage of development battery technology improved significantly and issues regarding the safety of lithium ion batteries became more clear. We entered into collaboration with a battery

manufacturer to develop new battery modules. Based on their performance and wide spread use we selected Panasonic batteries that are commonly used in computers as the core of our battery module. With the company we gained approval to combine these batteries into sticks, with 8 batteries per stick, thus providing the power that we needed to operate the DTSP. These sticks were assembled by the company and a control board was attached to regulate the charge/discharge rate and protection of each cell with in the stick. The sticks were then incased in a polycarbide tube for pressure protection and safety and then 6 of these stick were incorporated into a battery module (shaped in a triangular form and made of aluminum). This shape was used to allow the battery modules to be mounted to the DTSP around the shape of the scuba tanks, thus not effecting the footprint (drag) of the system and the divers metabolic cost of swimming. Characteristics of the system:

- Safety circuitry protects against:
 - Over-charge voltage (33.6VDC +/-0.3VDC)
 - Over-discharge voltage (26.0VDC +/-0.8VDC)
 - Over-current (1.2A charge, 3A discharge)
 - Over-temp (55C charge, 60C discharge)
 - Balancing on individual cell level (+/-1%)
 - Short circuit
- Nominal voltage 29VDC average
- Nominal current 1.1Amps for 2.2Amp hours
- Sticks connected in parallel bus for increased dive times and current-carrying capacity.

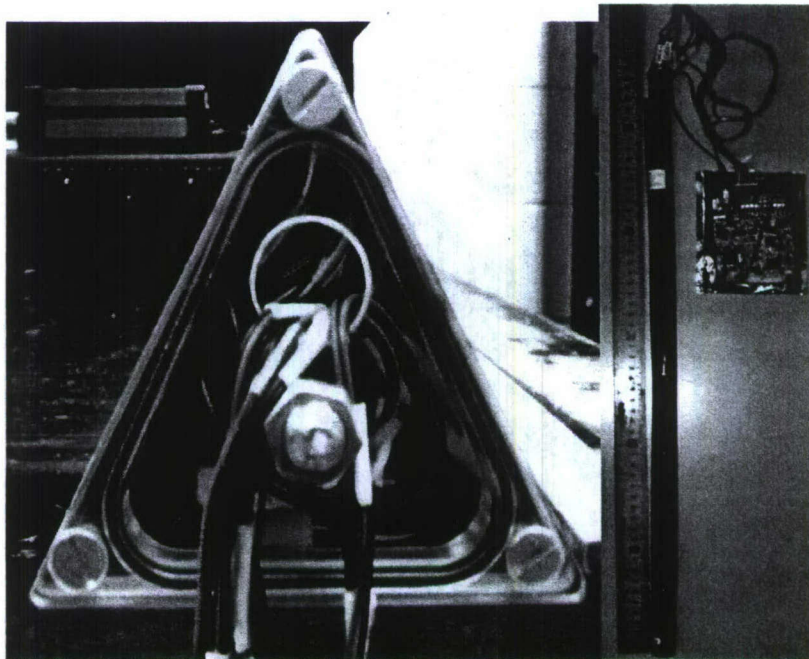


Figure 6. The battery “stick” made of 8 batteries is shown on the right and the triangular battery module on the left.

While our major aim was for that of a free swimming diver, we also wanted to accommodate the capability of this system to be used by surface supplied divers. This was based on the fact that the DTPS would provide better thermal protection to surface supplied divers than the current systems being used. To this end we developed a power supply system that had ground fault interruption capabilities and with a power cord could power the DTPS with 32volts DC. This system has been constructed and tested in un-manned and manned divers has performed very well.

Finally the DTPS must perform at depth (350 fsw was the target). This would require a backpack that was made of metal of sufficient thickness and shape to withstand the pressure, or alternatively, the system would have to be pressurized. We selected the latter approach to minimize the weight of the system in air and make it more ergonomically friendly. This system has been developed and is part of a Masters thesis by an engineering student (Marrouw E.) who will graduate in the summer of 2008. The system has been tested to the depth of 350 fsw successfully.

The most important accomplishment of this project is the performance of the DTPS in protecting divers in water temperatures from 5-40°C at rest and during exercise wearing a standard wet suit. In Figure --- diver's temperatures are shown unprotected in a wet suit, showing that they are under thermal stress in both cold and warm water.

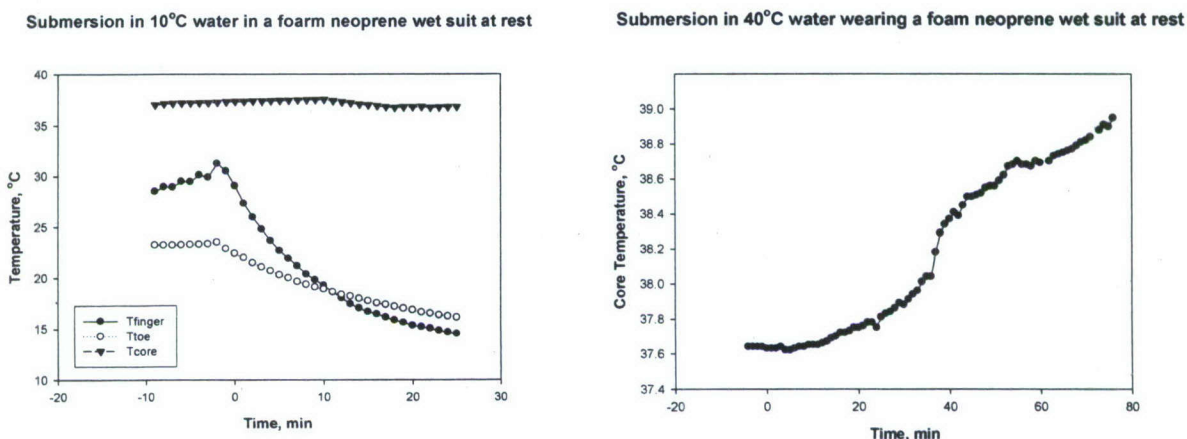


Figure 7. In the left panel, core and digit temperatures are plotted as a function of time for a diver only in a wet suit in cold water showing the reduced digit temperature. In the right panel is the rapid rise in core temperature of a diver in a wet suit in warm water. Both are unprotected.

The data from an experiment in cold water (left panel) and hot water (right panel) are shown below (figure 8). As can be seen the diver's core temperature is maintained at pre-immersion levels (37°C) while the skin temperatures are kept between 25 and 35°C, thus meeting the criteria of diver thermal protection. The power requirement by zone is shown in Figure 9.

In addition to protecting divers as shown above these experiments also allowed the determination of the power requirement to keep the diver protected, as well as the electrical power required. These data are shown in Figures 10.

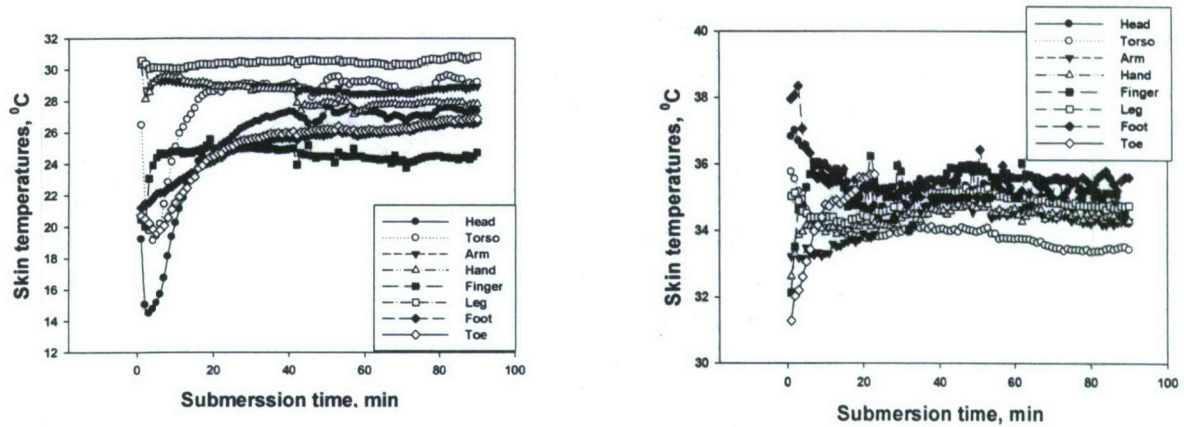


Figure 8. Core and skin temperatures are shown for subject using the DTSP in cold (left) and hot (right) water. All temperatures in the steady state were maintained in the desired range.

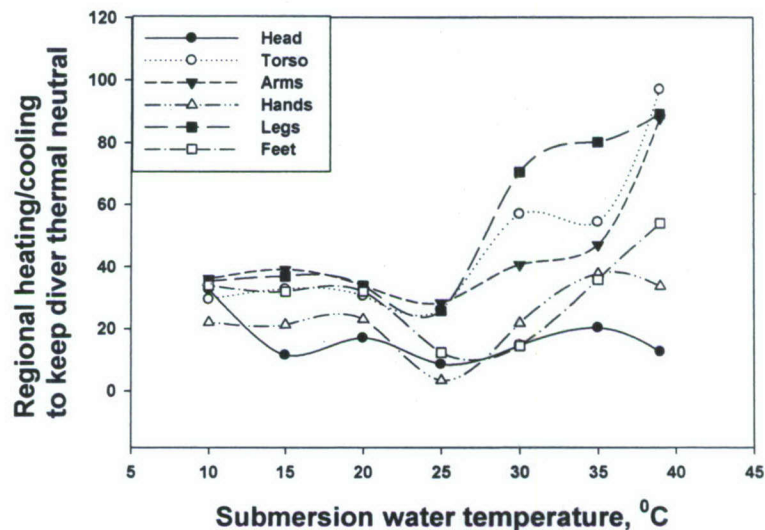


Figure 9. Power to heat/cool the diver as a function of submersion water temperature is shown for the six individual zone indicating that the % requirement per zone is similar at all water temperatures.

Finally these experiments allowed us to determine from the power requirement the number of battery modules that would be needed to protect divers in various water temperatures as shown in Figure 11. These data show that in cold water 5 battery modules would last 8 hours, while in hot water it would take 10 battery modules to last 4 hours. The differences are due to both the thermal load on the subject and the differences in heating (100%) and cooling (40%) efficiency of the thermal electric coolers.

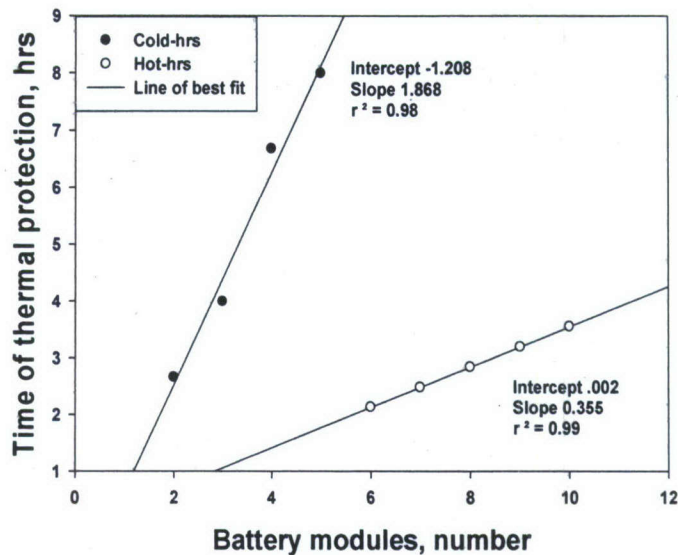


Figure 11. The time that thermal protection could last as a function of the number of battery modules the diver wore in cold and hot water.

CONCLUSIONS: The primary conclusion from this project is that divers can be protected from thermal stress in water temperatures from 5-40°C by the Diver Thermal Protection System developed and tested in this project. The goal of this project was to develop a system that could protect divers that could subsequently be applied to various diving scenarios. To this end we solved the most difficult scenario first, namely that of the free swimming diver. The DTPS can be battery powered utilizing the battery modules developed under this grant. In addition the DTPS can be powered from many other sources, including room power, generators, marine batteries etc, thus has the capability of being used in many different diving applications and environments. Importantly, the DTPS system can automatically protect divers in both cold and hot water, in the latter case this is the only system currently available to provide this protection to divers. The DTPS is currently available for commercialization. All aspects of this project have been patented or have been applied for by the University at Buffalo, and we are negotiating with companies to transfer this technology to make it available for purchase by the Navy.

SIGNIFICANCE: Although the Navy is currently conducting missions in cold and hot water these environmental conditions have to be planned into the mission and in many cases limit the capabilities of these missions. The Navy has many different diving environments and scenarios that have to be met. The significance of this project is for the first time many personnel have the potential to eliminate thermal stress as a planning parameter in mission planning.

PATENT INFORMATION:

- (4) Patent number: 10/645,726 Process for enhancing material properties and materials so enhanced. US Patent No. 7,101,607, Issued 9/5/2006.
- (5) Patent Application Serial No. 11/126,011, Filed May 10, 2005 for BODY THERMAL REGULATION/MEASUREMENT SYSTEM claiming priority of Provisional Application Serial No. 60/569,703, filed May 10, 2004. Inventors Mollendorf/Pendergast: R-5870; NP Reference No: 19226/2391

AWARD INFORMATION:

1. Nominated for Inventor of the Year Niagara Frontier Intellectual Property Association 2007
2. Albert R. Behnke Award for outstanding scientific contribution to advances in the undersea or
3. hyperbaric biomedical field 2006
4. Honoree of the SUNY Research Foundation for Innovation, Creation & Discovery 2005
5. Exceptional Scholar Award for Sustained Achievement at University at Buffalo 2004
6. Nominated for Inventor of the Year Niagara Frontier Intellectual Property Association 2000

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4. Erik Bardy Joseph Mollendorf, David Pendergast. Active Heating/Cooling Requirements for Divers in Water at Varying Temperatures Heat Transfer 2007 (Abstract 1226). ASME-JSEE Thermal Engineering and Summer Heat Transfer Conference.
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